AIAA 2001-5280

A Process for Tracking and Assessing Emerging Technology Development Programs for Resource Allocation

Michelle R. Kirby, Dimitri N. Mavris, and Matthew C. Largent
Georgia Institute of Technology
Atlanta, GA

1[st] AIAA Aircraft Technology, Integration, and Operations Forum
October 16-18, 2001
Los Angeles, CA

A PROCESS FOR TRACKING AND ASSESSING EMERGING TECHNOLOGY DEVELOPMENT PROGRAMS FOR RESOURCE ALLOCATION

Dr. Michelle R. Kirby, Prof. Dimitri N. Mavris[†], and Mr. Matthew C. Largent[††]

Aerospace System Design Laboratory (ASDL)
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

ABSTRACT

This paper discusses a quantitative process to track the progress of technology developments within an organizational structure. The process accounts for the temporal aspects of technology development programs such that technology portfolio assessments, in the form of technological progress towards organizational goals, may be monitored and assessed. Progress tracking of internal research and development programs is an essential element to successful strategic endeavors and justification of the pursuit of capital projects. The process discussed herein incorporates traditional methods for technology portfolio assessments with an amalgamation of quantitative assessments (tracking) and qualitative information (monitoring) while utilizing various modern design techniques, and is called the Technology Metric Assessment and Tracking process. Application of this process would provide a quantitative technology portfolio assessment to substantiate a company's strategic investment plan over the life of various product design cycles such that the maximum payoff of technology investments may be pursued and the associated risks monitored.

MOTIVATION

Some guiding principles for any successful organization are to create a solid strategic plan for the future and, subsequently, track and monitor the progress of said investments to the overall goals of the organization. Subsequently, a solid strategic plan must guide the decision-making process for all long term spending ventures. "Strategic planning can be defined as a structured process through which an organization translates a vision and makes fundamental decisions that shape and guide what the organization is and what it does."[1] The strategic plan is then compiled into a decision package, in the form of a business case, to justify capital project endeavors. A solid plan includes documentation and analysis that support the proposed investment opportunities, especially with regards to technology development programs and how the technology programs support the strategic goals of the organization. Effectively, the business case guides Research and Development (R&D) investment decisions such that new products are competitive or superior to existing product lines.

Once the strategic plan is accepted and pursued by the organization, the progress towards the strategic goals must be monitored and tracked to ensure that the expectations are being met within budget and schedule constraints while achieving performance goals. The progress of the strategic plan should be assessed quantitatively (program tracking) and qualitatively (program monitoring).

The process developed herein to address these issues is called the Technology Metrics Assessment and Tracking, or TMAT, process. The foundation of the process is rooted in the technology metrics tracking program initiated in NASA's High Speed Research program in the late 1980's [2]. Building on this initial framework, the technical approach will address the stochastic (time-varying probability) nature of a technology development program with respect to performance progress, development schedule, and budget allocations within an organization's strategic plan. In addition, probabilistic design techniques are utilized to accurately capture the uncertainty associated with immature technology impacts to the organization's strategic goals.

* Research Engineer II, Aerospace Systems Design Laboratory (ASDL), Georgia Tech, Member, AIAA.
† Boeing Chair for Advanced Design, School of Aerospace, Director, ASDL, Senior Member, AIAA.
†† Graduate Research Assistant, School of Aerospace, Director, ASDL, Student Member, AIAA.

APPROACH

The TMAT process is an evolved version of the HSR metrics tracking process and the Technology Identification, Evaluation, and Selection (TIES) methodology [3]. The coupling of these methods will provide a means to substantiate R&D investments and optimally allocate resources to the largest payoff technologies to meet the organization's strategic goals. The TMAT process is broken into five major steps:

- Technology metric identification
- Technology audit scheme definition and information gathering
- Technology metrics assessment
- Technology metrics integration
- Technology metrics sensitivity assessment

Each area of the TMAT process is described in addition to the information requirements and the potential results of application. The successful application of the TMAT process will be highly dependent on the information that can be obtained from the technology experts within the organization. As a consequence, a void of required information will result in a loss of technology tracking fidelity. However, prior to the description of each step in the TMAT process, a few definitions are needed for the edification of the intended reader.

Metric: a standard of measurement
System metric: a standard of measurement used to judge the goodness of the system, equivalent to a figure of merit
Technology metric: a standard of measurement used to define the impact of a technology on the system; may be either a benefit or degradation to the system
Technology expert: a person intimately involved with the development of a specific technology, in general, a disciplinarian
Expert opinion: qualitative or quantitative information elicited from the technology expert through interviews or paper questionnaires
Uncertainty: a falling short of certainty to an almost complete lack of conviction or knowledge, especially about an outcome or result
Technological uncertainty: a lack of knowledge of the impact of a technology on the system, or product, of interest due to technological immaturity
Immature technology: a technology in varying levels of development, as defined by a readiness level, where knowledge increases and uncertainty (or risk) diminishes with increasing maturity
Technology Readiness Level (TRL): a measure of the major milestones of technology maturity as defined by a qualitative scale ranging from a Level 1, where the basic principles of a technology are observed, to a Level 9 where the technology is applied to a product that has entered into service [4]

As a clarification point relevant to industrial organizations, within a government funded development program, a technology is typically matured to a TRL of 6 and subsequently transitioned to industry. The development from a TRL of 1 to 6 is executed in isolation of a specific system, although the potential application may be known. The development from 7 to 9 is associated with technology integration into a relevant system or product. This can be compared to the Research, Development, Testing, and Evaluation efforts made by a company when a technology is infused to an operational system. Recognizing that this integration effort is in some ways substantially different than the initial technology development effort, the TRLs from 7-9 have at times been referred to as Integration Readiness Levels. However, within the context of the current discussion, the technology developments will be considered as continuous in-house developments, such that the TRL discontinuity will not be an issue.

TMAT Step 1: Metrics Identification

The first step in any program monitoring or tracking process must be to define the problem at hand. Specifically, the technology metrics that will be quantitatively assessed and tracked through the life of the strategic plan must be identified in an Integrated Product Team (IPT) working meeting(s) format. This step may be repeated if the strategic goals were to change as the program progresses or if different goals were identified at a later date. Three objectives of this step include:

- Identify the key personnel who have the appropriate level of knowledge regarding the organizational structure of the strategic plan and the constituent elements.
- Formulate the organizational structure into a hierarchical decomposition to identify the technology metrics, a top down assessment approach.
- Identify the potential system platforms (or vehicle applications) in which the technologies will be infused and assessed.

To set the foundation of the appropriate metrics to be used in the TMAT process, a set of possible metrics must be identified. To accomplish this end, the key personnel involved in technology development, metrics integration to the systems, and technology evaluations must come together in an IPT format. The objective of the IPT is to perform a top down decomposition of the strategic goals into the fundamental metrics, such as design or technology metrics. *Brainstorming and affinity diagrams can be used to facilitate information generation and the dependencies of contributing factors*. Additionally, the IPT *must agree upon the potential system platforms* (aircraft or vehicles for which the technologies will be infused) such that the most generic decomposition may be defined that could capture any technology or system application.

Once the goal decomposition is completed, the dependencies of the different levels may be organized in a Relevance Tree format. A partial example for a strategic goal of CO_2 reduction with the taxi fuel decomposed is shown in Figure 1. Once the Relevance Tree is populated, analysis tools or qualitative scales to be utilized at each level of the Relevance Tree must be established by the IPT. The rationale behind the identification of the tools or scales is to determine which metrics defining a technology impact may be rolled up to the strategic goal level. If there is no direct quantitative link between a technology metric and the strategic goals, then a technology must be classified as a *monitored technology*, that is, no quantifiable method exists to establish an explicit rollup to the strategic goals.

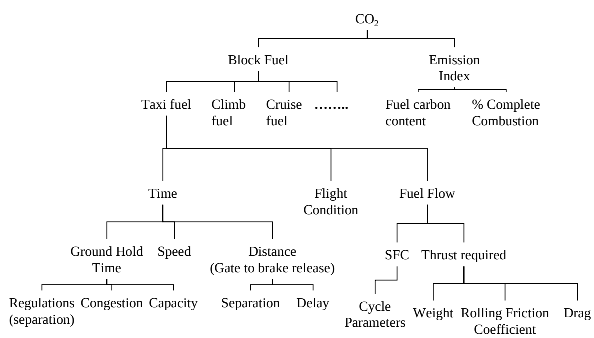

Figure 1: Example Relevance Tree

TMAT: Step 2: Technology Audit

The key to success of any R&D technology program tracking and monitoring scheme is based on the information that can be obtained from the individual technology programs. Specifically, a detailed and objective evaluation and description of the explicit technology development programs must be established. To accomplish this end, information must be elicited from the appropriate personnel associated with each technology development program (or technology experts) and may be accomplished via the Delphi method [5]. The Delphi method is a structured means of incorporating expert opinions (usually subjective) through questionnaires and controlled feedback to estimate a technology impact and the confidence of achieving that impact [6]. The questionnaire may take many forms including face-to-face interviews, a postal questionnaire, or a set of written questions to be self-administered [7]. The latter form of the Delphi method is a popular approach for information gathering in the aerospace community and can be organized in a web-based or a spreadsheet format. Either vehicle for information gathering should provide the necessary descriptions and data to track the technology and schedule progress impact on the overall company strategic goals.

However, each of these schemes can be confronted with mixed acceptance from the individuals (technologists) supplying the information. With both schemes, the description of the information desired can be ambiguous and the person supplying the required information may be, at times, unsure as to the appropriate response to a question. Although attempts cab be made to provide guidance for the responses, uncertainty still prevails in the form of subjectivity and biases of the responses and an inability to extrapolate the impact of a technology to other potential applications.

In addition, there exists a deeply rooted psychological dimension of eliciting information from individuals in any environment. Specifically, a few roadblocks may be encountered during the information gathering. These roadblocks include biases of responses, required time to determine the necessary information due to overburdened individual work schedules, misunderstanding of information desired, lack of motivation for increased work load, ad-hoc approaches to technology development in lieu of a structured and logical development plan, organizational inertia, and so on. Although not all of the roadblocks can be eliminated, eliciting information from individuals must account for the potential stumbling blocks through iterations and accountability of the responses from the technologists' back to the decision makers.

To accomplish this end, a Technology Audit scheme for distribution to the appropriate technology experts should be created. The Audit scheme should be repeated annually, and possibly biannually, to gather the necessary information for the tracking and assessment of the strategic goals. The focus of information needed will be in four general areas regardless of the specific format or wording, including technology and metric definition, current technology impact levels, forecasted technology impact levels, and planned activities and general budget information, each of which is described in more detail. This element of the TMAT process is the most essential aspect for accurate and proper tracking of the technology portfolio as will become evident.

Audit Focus 1: Technology and Metric Definition

The first focus of the Audit scheme is to identify and define the technologies and associated metrics. Areas of information pertaining to this focus include technology definition and description, technology metric identification and goals, and development program specifics, in terms of experimental set up or analytical assumptions.

The definition of the technology includes the name of the technology and where the technology is in relation to the company's work breakdown structure for identification purposes. The description of the technology should include a detailed explanation of what the technology is, how it works, what part of the product it affects (including benefits and degradations), what operational regions are applicable (for example, supersonic, subsonic, and so on), and what enabling technologies are required for infusion. This information is used for bookkeeping purposes and to develop an understanding of the functionality of the technology.

Next, the identification of the specific technology metrics that define the technology impact must be provided, along with the end of program (EOP) goals and direction of desirability (i.e., maximizing preferred over minimizing). This focus element determines if the technology metrics identified by the "experts" fall into the rollup scheme of the Relevance Trees from Step 1 of the TMAT process and this information is used in later steps for technology mapping. Finally, specific information regarding the development program structure is desired, including:

- Experimental or analytical development to establish how the metric is measured
- Experimental setup or analytical assumptions to determine if scaling laws should be established
- Potential applications to other systems and varying impacts

The rationale behind this focus element is to gain an understanding of the development process of the specific technology. In traditional experimental setups, reduced scale demonstrators are utilized to decrease costs and expended development time and manpower. Subsequently, the results are subjectively scaled to full-scale prototypes for system evaluations. However, this approach may not be suitable for a business case with a multitude of systems (or products) and operational conditions in which the technologies may be infused. Potential solutions to this dilemma include testing or experimenting the technology at the proper test conditions (e.g. Reynold's number) or using a small-scale experiment to calibrate an analysis tool, which could then be scaled to full-scale conditions.

Further, the traditional approach to a development program tends to be ad hoc. For example, a technologist may pursue a technology by directing the development based on results from the following question: *if I change this, what happens*? In general, this causes a random approach towards the progression of the technology to be pursued and tends to be costly and time consuming. A more efficient approach would be to develop an *intelligent development program plan* based on a detailed breakdown of the potential sources of variability of the technology. Once the sources of variability or uncertainty were identified, then a methodical approach, such as Design of Experiments, could be used to plan the experiments needed to reduce the uncertainty. This approach would yield the maximum information with minimum expenditure, regardless of the development technique, i.e., experimental or analytical. However, it is necessary for the TMAT process to track progress in all technology development efforts, however they are planned.

Audit Focus 2: Current Technology Levels

The next focus of the Technology Audit scheme is to obtain the reference point of departure, that is, the current technology impact levels that can be obtained by the given technology, and the current TRL. The information that is desired from this focus is to establish the current state of the art in the technology area and the level of maturity. For example, a technology is being developed that can increase the compression ratio across a compressor stage by 15%. An obvious question arises: a 15% increase with respect to what system and flight or operational condition? Further, the 15% increase is a goal for the EOP and may or may not be achievable at the present time. Thus, the information required from this focus is to quantify the impact that the technology would have on the system *if* it were infused today at the current maturity levels with an associated confidence level. For example, the goal of the technology would be a 15% increase in compression ratio. However, through the experiments performed to date, approximately 7% can be achieved with the worst case being 5% and the best case being 16%. In addition, potential detrimental effects of the technology must be estimated to accurately assess the impact of a technology. All to often, pure benefit assessments are performed to judge the 'goodness' of a technology. However, the degradations due to integration may, in some instances, far out-weigh the benefits and deem the technology unworthy of further development.

Traditional technology audits have collected either one number (the target) or possibly three numbers (max, min, and most likely) for the metric value. However, the TMAT process requires the maximum, minimum, and most likely value of the technology metric(s) due to the progress to date and the confidence in the predictions given. These four values can then be used to define a Beta distribution, a probabilistic representation of the impact information given. One should note that the information collected in this focus pertains to the estimated *current state* of the technology, <u>not</u> the forecast value. Obviously, the current value is subjective since the technology is not being used on an actual system. Nevertheless, tracking the estimated current value allows for better forecasts of future progress and better tracking of progress to date and at future decision points.

Audit Focus 3: Forecasted Technology Levels

The objective of Focus 3 is to collect information on the forecast metric values, both benefits and degradations, for the technology at the EOP. This information will show how the predicted value matches up with the target value, and is important in determining a future estimate for the technology development over time. As will be discussed further, Beta distributions will be created from the metric levels in the same method as for the current values, ensuring consistency in the technique. The metric distributions will be used to show the probability of reaching the target values, to track the changes in the future estimated value, and to anchor the projection done using the current values for each year by giving a final, EOP value.

Additionally, forecasting the impact of any future technology must consider the degree of difficulty in achieving a particular technology development goal. Mankins suggested a degree of difficulty scale, similar to the TRLs, to capture this aspect and is called the Research and Development Degree of Difficulty ($R\&D^3$) [8]. The $R\&D^3$ metric is a subjective measure of how much difficulty is expected to be encountered in the maturation of a particular technology. Unlike typical risk factors of high, medium, and low, the $R\&D^3$ is a intelligible description of the difficulties that must be overcome to develop a particular technology. The $R\&D^3$ scale is complimentary to the TRL metric and consists of five levels varying from a Level I (low degree of difficulty) to a Level V (very high degree of difficulty). A potential use of the $R\&D^3$ value in the TMAT process could follow the idea generated by Mankins [9]. The $R\&D^3$ could be mapped to a quantitative scale that would be a measure of the likelihood of achieving the EOP goals. The uncertainty associated with the technology impact would be amplified by the anticipated difficulty of the technology maturation process and measure the possibility of technical failure of the specific technology development program.

Audit Focus 4: Activities and Planned Schedule/Budget

One of the primary purposes for technology development is the reduction of risk or uncertainty involving performance and cost of a given technology. This is accomplished with studies, both analytical and experimental, that attempt to nail down the details of how a technology behaves. These studies should be planned in such a way as to identify the main sources of uncertainty (or risk) in the technology and to directly address those specific uncertainties. Experiments, or formal risk management plans, can be used to mitigate risk, for example, risk of failure of a technology program and minimum success criteria. Some may be classified as uncertainty risk, and this is best dealt with by identifying the areas of uncertainty and quantifying that uncertainty and its affect on the strategic goals. The approach taken herein is to quantify the risk associated with the technology development plans and propagate those risks. Three main areas of uncertainty risk can be identified: performance, time (equivalent to schedule), and cost. Performance uncertainty risk (or simply, uncertainty) is already being addressed through the earlier phases of the metrics tracking process. Cost and schedule risk, however, are herein addressed.

Schedule risk is important since time overruns can affect the completion of the major tasks for the development program. It is important to identify the "critical path", which is the path through the schedule that takes the most time, and therefore the most likely to extend beyond the limits of the program. Typically, this critical path may be identified in a discrete manner using a Gantt Chart or Precedence Chart. This is not the most realistic method to address the problem, since it does not account for the uncertainty associated with the time necessary for individual activity completion. The addition of uncertainty creates an environment where there are a number of possible critical paths, each of which has an associated probability.

Budget uncertainty is also a critical measure that should be considered for proper technology tracking. At the individual technology level, there is uncertainty involved in the cost (or budget required) associated with the completion of key, or high priority, tasks. If it is assumed that there is a fixed amount of work to be done, then the cost associated with that work might be considered to be discrete. This is rarely the case as there are usually unexpected difficulties that arise or even significant technological breakthroughs required, both of which can have significant effects on the cost associated with the completion of that activity. It is then reasonable to deal with the required budget for an activity as a probabilistic value similar to the way schedule was addressed. If each activity's budget is addressed in this manner, then the strategic plan budget can be viewed as probabilistic in nature.

Assuming an existing, discrete schedule of activities and costs have been determined, it is possible to convert the schedule into an activity network diagram. This is a project management tool, similar to the Precedence Chart, which gives a list of activities and milestones/events, and graphically depicts how these activities fit together. A number of analysis tools have been created to analyze these diagrams, one in particular is the Venture Evaluation and Review Technique (VERT). VERT was created in the early 1970's to address perceived shortcomings of other network techniques available at the time [10]. VERT allows probabilistic network modeling of time, cost, and performance, and allows interaction between these areas and is useful for both project management and risk analysis [11,12]. The probabilistic modeling provides the ability to quantify the schedule and cost uncertainty associated with a given project, or in this case, a technology development program.

TMAT Step 3: Metrics Assessment

The focus of this step of the TMAT process is to translate the information obtained from the Technology Audits to a useful form for quantitative assessments. However in some instances, the technology programs may be limited in results or the impacts may not be quantifiable or measurable on an annual basis. Thus, the TMAT process accounts for this situation with a classification of the types of technologies to be tracked or monitored. The technologies that can be tracked will then be mapped into an amenable form for quantitative assessments. The results of the translation of the technology impacts must have a controlled feedback to the originators of the technology information to ensure the qualitative descriptions match the mapped quantitative impacts to be used in the TMAT process.

Technology Classifications

A technology classification is based on the description of the technology metrics and whether or not the metrics roll up to the strategic goals as identified from the Relevance Trees in Step 1. If a technology can be quantified by some analytical means and shows a direct relationship to the strategic goal, the technology is deemed as a *tracked technology*. However, if this is not the case, the technology is considered to fall into the classification of a *monitored technology*. In addition, some technologies may not have annual results of development progress with respect to the specific metrics. Thus, a potential scheme for monitoring those technologies may be the percentage completion of the required activities to reach a particular TRL.

Technology Mapping

The technologies deemed as trackable from the Audit sheets will be mapped into a useful form for quantitative assessments in Step 4. The mapping entails extracting information from the Audit sheets and defining the following:

- Creating technology vectors that describe the impact on the systems or products
- Creating a Technology Impact Matrix (TIM)
- Defining the appropriate distributions to represent technological impact uncertainty
- Defining a Technology Compatibility Matrix (TCM)
- Creating activity networks of the individual technologies

Technology Vectors - For each technology funded or pursued within the organization, a capability must exist to quantify the technology impacts. The technology metrics, which defined the impact of the given technology, can be combined into a technology vector, $\vec{k}$. The elements, k_i, of the vector constitute the impact of the specific technology on a specific disciplinary metrics. Each element of the vector has an estimated impact value as established via expert questionnaires, as derived from experiments or physics-based modeling [13]. For example, a technologist is developing an arbitrary technology (T1) that is expected to increase cruise drag by 4% (k_{drag} = +4%) while reducing Operation and Support (O&S) costs by 1% ($k_{O\&S}$ = -1%) and RDT&E costs by 2% ($k_{RDT\&E}$ = -2%). The incremental percent changes are *relative to a datum point or a baseline value as declared by the technologist*. Another technologist is developing a technology (T2) that will reduce fuel burn by 3% ($k_{fuel\text{-}burn}$ = -3%) and O&S costs by 2% ($k_{O\&S}$ = -2%). One may cross-reference the elements of each technology vector to establish a common set. Thus, the common set defines a *generic technology impact vector*, T_i, for which all technologies under consideration may be defined. In the example above, the generic technology impact vector would be a function of drag, fuel burn, RDT&E costs, and O&S costs, such that $T_i = f\,(k_{drag}, k_{fuel\text{-}burn}, k_{RDT\&E}, k_{O\&S})$. Not all technologies will affect each element of the generic vector, but the vector must capture all the disciplinary metrics that the technologies influence. For T1, the generic vector would become

$$T1 = f(k_{drag}{=}{+}4\%, k_{fuel\text{-}burn}{=}0\%, k_{RDT\&E}{=}\ {-}1\%, k_{O\&S}{=}\ {-}2\%)$$

When multiple systems are considered for infusion, the impact vector for a given technology *may not* be consistent across platforms. To accommodate this situation, a new derivative technology vector should be defined, T1′, which describes the impact of T1 in the new system or operational regime. Additionally, using this nomenclature ensures proper tracking of the impact of like technologies across multiple systems.

<u>Technology Impact Matrix</u> - The technology vectors can be combined into a Technology Impact Matrix (TIM). Although the values in the TIM are deterministic, the proper shape of the technological uncertainty is incorporated during the evaluation step. Deterministic values are used in the TIM for presentation purposes only.

<u>Technological Uncertainty Representation</u> - The identification of the appropriate form of uncertainty modeling for the technology impacts is based on the information obtained from the technologists. A Beta distribution is created using a technique proposed by Batson [14]. The Beta distribution is defined by three parameters including a scale factor as well as two shaping parameters, α and β. Batson created a method for converting typical expert opinion information (maximum, minimum, and most likely values as well as a confidence level) into the parameters needed for a Beta distribution [14]. The translation of this information into the Beta distribution parameters is depicted in Figure 2. To ensure that the distribution created is a realistic representation of the opinion of the technologist; an iteration scheme should be devised to elicit feedback from the appropriate "experts". As these distributions are created each year, they can be used to forecast the future progress of the technology. The updates will then affect the forecast, reducing the uncertainty and changing the shape, as more information is known.

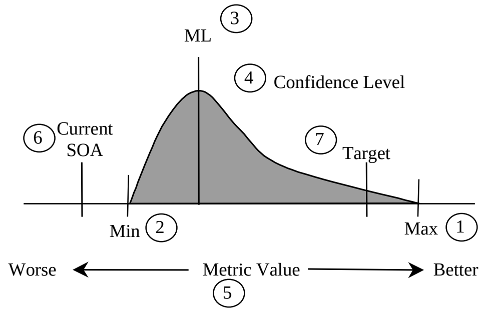

Figure 2: Beta Distribution and Defining Values

The following information is used to create the distributions at current and forecasted levels:

1. Maximum value of metric
2. Minimum value of metric
3. Most likely value of metric
4. Confidence level in estimates (5 possible levels)

These values help with interpreting the distribution created:

5. Direction of metric improvement
6. Current State of Art (SOA)
7. Target value for metric

Each element of the technology vector is assigned the appropriate Beta distribution based on the information obtained from the Technology Audit scheme. The primary use of the two distributions is to track the uncertainty of the technology programs over the life of the strategic plan and establish the technological progress to the EoP goals. A pictorial of the combination of the distributions, at current and EoP levels, is shown in Figure 3. The payoff of the application of the TMAT process is to establish the technology improvement over time such that the progress towards the end goal of the technology impact may be monitored on a frequent basis. If a technology falls behind schedule, the decision makers may question the worthiness of continued funding or identify risk mitigation techniques to assist the particular development program.

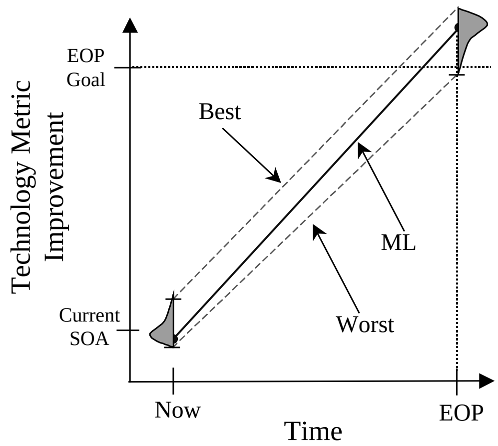

Figure 3: TMAT Process for Tracking Technology Impacts over Time

Technology Compatibility Matrix - With the technologies specified, physical compatibility rules between technologies are established and formalized in a Technology Compatibility Matrix (TCM). A group of technologists or disciplinary experts familiar with the intended function and application of each technology best prepare this matrix. Incompatibilities arise when technologies are *competing* to perform the same function, one technology *severely degrades* the intended function or integrity of another, a technology becomes *obsolete* at a given time, or the technologies are only applicable for a specific product application or operational regime. Additionally, one could have another measure that included enabling technologies such that a technology is not physically realizable without an additional technology being developed.

Technology Activity Network Diagrams - The activity information gathered must be used for two purposes: create the actual activity network diagram, and populate that diagram with probabilistic values. The first part involves using the order of completion of the activities, as well as the form of the relationship (series, parallel, or combination of both) to diagram the proposed flow of the technology development process. The second part involves taking information gathered on the time and cost incurred for the activities and transforming that information into probability distributions. The ideal situation would be to use the Batson's method described previously, but there are many other techniques available. The diagram and probability distributions are then transferred into the form of a VERT input file. Largent and Mavris describe this approach in more detail [15].

TMAT Step 4: Metrics Integration

The focus of Step 4 of the TMAT process is to quantitatively assess the various technology impacts on the organization's strategic goals. In the various stages of product design, a rapid assessment is desired so that trade-offs can be performed with minimal time and monetary expenditures. The advent of the computer has greatly facilitated this objective via Modeling and Simulation (M&S) environments. The Defense Systems Management College states that use of an M&S environment provides four benefits to the design process and includes cost savings, accelerated schedule, improved product quality, and cost avoidance [16]. Hence, the goal of Step 4 is to create a physics-based analytical environment whereby the impact of the technology metrics to the strategic goals may be quantitatively assessed. This approach has been implemented numerous times [3,6,13,17] and only a summary is discussed for brevity.

The M&S environment is used to create metamodels (i.e. Response Surface Equations) of the strategic goals as a function of the technology metrics. The range of validity of the metamodels is defined from the TIM at the current and EOP levels. The resulting metamodels then can be used to evaluate the effects of the technologies through the technology vectors. The combinations of the technology effects are then treated probabilistically by applying the technology vector distributions established in Step 3. Since metamodels are present, the probabilistic treatment of the problem is done through a Monte Carlo simulation. The end products of this probabilistic treatment are cumulative distribution functions for each strategic goal due to each technology combination.

TMAT Step 5: Metrics Sensitivity Analysis

The final step of the TMAT process is an examination of the various technology impacts on the overall strategic goals. As a result of the previous steps, the information obtained regarding the impact of the technologies is enormous. A plethora of viewpoints can be considered including multivariate technology metric sensitivities to the strategic goals, confidence of achieving said goals via uncertainty assessments, payoffs of technologies across multiple platforms, and budget profile trade-offs. Each of the view points can be post-processed into a plethora of formats for visualization of the results, including waterfall charts, technology metric tracking sheets, or bar charts of individual technology contributions.

Metric Sensitivities

One of the primary results from the TMAT process is the identification of the highest payoff technologies that are contributing to meeting the strategic goals. This information is a direct result of the Metrics Integration approach and may be visualized with the dynamic Prediction Profiler feature in the statistical package JMP® created by the SAS institute. The power of depicting the sensitivity representation in this fashion is the ability to instantaneously show how the technology impacts interact with one another and also the goals. This is extremely useful in *providing the decision-maker a visual means by which informed decision can be made and justification of investment decisions*. One may change whether a technology is "on" or "off" the system and instantaneously see the impact on the goals. Static representations could be incorporated into a report format, while a dynamic environment could be more appropriate for working meetings.

An example Prediction Profiler is shown in Figure 4 and depicts the *prediction traces* for each independent technology impact. The prediction trace is defined as the predicted response in which one variable (or technology) is changed while the others are held at their current values. The profiler shows the sensitivity of the goals to the input variables. In the dynamic environment, moving the vertical hairline with the mouse turns "on" or "off" the technology and JMP® recomputes the underlying metamodels and updates the prediction traces and values. Effects of the technologies in the Prediction Profiler are evaluated based on the magnitude and direction of the slope.

Additionally, the underlying metamodels of the Prediction Profiler may be used to translate the impact of the technologies into a plethora of other formats depending on the most amenable format for comprehension purposes. The technology sensitivities can be generated for each vehicle for which the technologies were infused and at various confidence levels.

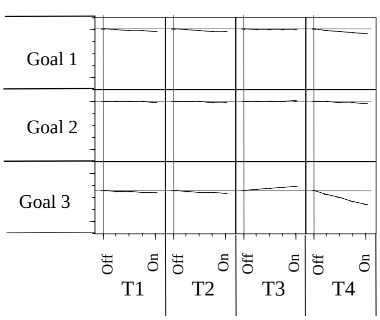

Figure 4: Potential Formats for Metric Sensitivities

Traditional methods of evaluating the impact of technologies only look at a point estimate with no insight into the associated risks. With the approach taken in the TMAT process, the risk associated with adding technologies is inherent in the process since each technology impact is modeled probabilistically. Hence, if a decision-maker desires a 90% confidence (or a 10% risk) of achieving a particular goal, the TMAT process provides the substantiated information upon which the decision can be made with confidence. Traditional methods do not. Additionally, if one considers only performance metrics without the implications of the investment costs associated with developing a technology, one would expect that the addition of more technologies would further improve the system. From the traditional perspective of point estimates and technology benefit assessments, this is true. However, once technological uncertainty is included in the assessment, the decision as to which technologies are more effective is based on a confidence level and the associated impact at that level.

How do the TMAT results from a probabilistic evaluation differ from a deterministic one? The answer is best described from a visual representation as in Figure 5. From a traditional deterministic assessment, the response (or goal) is a point value, depicted as R_i, and may be defined as the "theoretical" impact of a technology combination. When uncertainty is introduced, the impact of the technology on the response becomes uncertain as shown by the probability density function and can be defined by a mean and a variance. If a technology is not fully matured, i.e., TRL less than 9, then the performance improvement value anticipated from the technology is not fully realized. This is evident by the mean value of the response, μR_i, being shifted from the value where no uncertainty is included, R_i. *Thus, there is degradation, $\Delta\mu R_i$, in the response from the inclusion of uncertainty.* The probabilistic technology sensitivities may be established in the same manner as was performed in the deterministic evaluation, but for a given response, additional information must be extracted; the "certain" value, R_i, the change in the mean value, $\Delta\mu R_i$, and the standard deviation, σR_i. Hence, the impact of technology on a given response, R_i, can be defined as a normal distribution with a mean value of R_i,+ $\Delta\mu R_I$ and a standard deviation of σR_i.

Identification of Technology Payoffs

An additional goal of the TMAT process is to identify the most influential technologies across a range of potential products, such as a fleet of vehicles. If the payoffs of the technologies were considered in isolation, some technology impacts could be considered negligible and not worthy of further development. "Spider Charts" or radargrams for the different products would allow for visualization and justification of technology investments across vehicle platforms, as shown in Figure 6. The highest payoff technology combination is the set that maximizes the area across the different vehicles and strategic goals. In this notional example, the combination of T3+T7+T8 maximizes the area and would constitute the "best" combination of technologies for the company goals. Technological uncertainty can be represented as confidence levels around the deterministic radargram.

Finally, technology frontiers could be used for presenting the technology impacts. Technology Frontiers are defined as the limiting threshold of an "effectiveness" parameter, whereby uncertainty is captured and tangible results presented. An Effectiveness Parameter (EP) is a user-defined function for which maximization is desired and preference of the different goals is introduced through weighting factors as discussed by Kirby and Mavris [17]. The EP value for each technology alternative and vehicle could be established and compared to the required funding level (or current investment) to mature the set of technologies. Threshold limits may be placed on the EP and the investment amount. The two threshold limits define the largest payoff technology space with respect to performance, economics, or the entire system. The technology alternatives that fall within this region are easily identified and may be investigated in further detail. An example frontier is depicted in Figure 7.

Probabilistic Critical Paths and Schedule/Budget Rollup

One of the typical results from a schedule analysis performed for project management is a Critical Path analysis. An analysis of this type shows which activities, as a part of a complex schedule, lie upon the path that has the longest time for completion. These activities are examined to determine potential alternative paths to reduce the time necessary. Or, risk management methods are used to ensure that those activities do not run past their stated schedule and create schedule overruns. Due to the uncertainty associated with a development schedule on long-term projects, there is always the possibility that more than one critical path could be identified, depending on different possible completion times for individual activities. VERT runs a Monte Carlo simulation and can identify which activities were located on the critical path at different times, and provide the probability that a given activity will be on that critical path. This will allow project and program managers to apply risk management techniques to the activities with the highest probability of being critical, thereby resulting in lower overall program risk. Largent and Mavris provide a detailed explanation of this TMAT element [15].

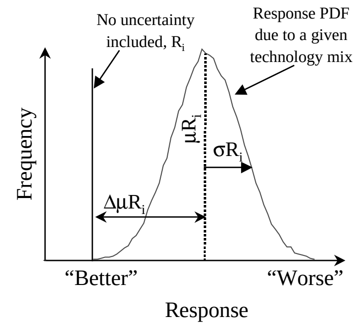

Figure 5: Impact of Technological Uncertainty on a Response

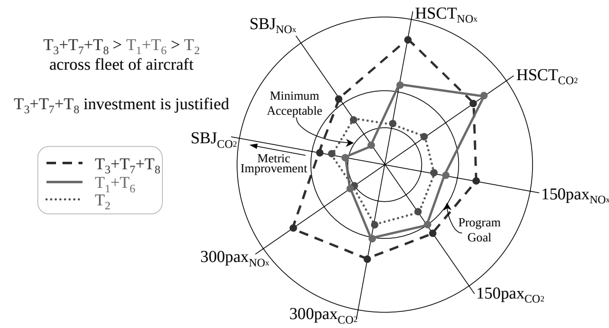

Figure 6 Radargram for Identification of Highest Payoff Technologies

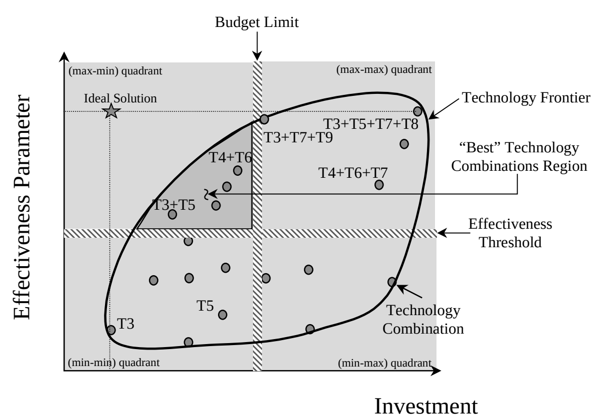

Figure 7: Notional Technology Frontier

SUMMARY

This paper described a process to assist an organization's capability to track and monitor sponsored technology development programs contained within a strategic business plan. The application of the process allows for a stochastic program management technique to assist in allocation of Research and Development monies to achieve the company's strategic goals. Traditional technology assessment techniques were combined with modern probabilistic assessments to quantitatively assess and track the impact of a company's portfolio of technology development programs to the overall company objectives. The power of this approach is the accuracy, efficiency, and insight to a current technology portfolio and quantitative justification of investment decisions.

The development of the process contained herein was sponsored under NASA Glenn contract NAS-3-00179 entitled "UEET Program Metrics Implementation" and will be implemented on said program.

REFERENCES

1. Executive Guide: Leading Practices in Capital Decision-Making, GAO/AIMD-99-32, December 1998.
2. C.A. Ward, "Technology Tracking for the High-Speed Research Program," SAE Paper 985549.
3. Kirby, M.R., "A Methodology for Technology Identification, Evaluation, and Selection in Conceptual and Preliminary Aircraft Design," Ph.D. Thesis, Georgia Institute of Technology, March 2001.
4. Mankins, J.C., "Technology Readiness Levels," White Paper, April 6, 1995.
5. Burgelman, R.A., Maidique, M.A., Wheelwright, S.C., Strategic Management of Technology and Innovation, 2nd Ed., Irwin McGraw-Hill, Boston, 1988.
6. Kirby, M.R., Mavris, D.N., "Forecasting Technology Uncertainty in Preliminary Aircraft Design," SAE Paper No. 1999-01-5631.
7. Oppenheim, A.N., Questionnaire Design, Interviews and Attitude Measurement, Pinter Publications, London, 1992.
8. Mankins, J.C., "Research & Development Degree Of Difficulty (R&D3)," White Paper, March 10, 1998.
9. Mankins, J.C., "Integrated Technology Analysis Methodology (ITAM)," White Paper, February 21, 2000.
10. Thomas, T.N., VERT – A Risk Analysis Technique for Program Managers, Defense Systems Management College, May 1977, ADA047620.
11. Lee, S.M., Moeller, G.L., Digman, L.A., Network Analysis for Management Decisions, Kluwer Nijhoff Publishing, Boston, 1982.
12. Trier, N.H., Cost/Schedule Uncertainty Analysis for VADS Short-Range (RAM) Product Improvement Program, US Army Armament Materiel Readiness Command, Systems Analysis Directorate, February 1977, ADA039813.
13. Mavris, D.N., Kirby, M.R., "Technology Identification, Evaluation, and Selection for Commercial Transport Aircraft," SAWE Paper No. 2456, May 1999.
14. Batson, R.G., Love, R.M., "Risk Analysis Approach to Transport Aircraft Technology Assessment," *Journal of Aircraft, Vol. 25, No 2*, February 1988, pp 99-105.
15. Largent, M.C., Mavris, D.M., "Modeling of Cost/Time/Performance Risk in Technology Development," AIAA-2001-5258.
16. Defense Systems Management College, "System Engineering Fundamentals," Defense Systems Management College Press, Fort Belvoir, VA, October 1999.
17. Kirby, M.R., Mavris, D.N., "A Method for Technology Selection Based on Benefit, Available Schedule and Budget Resources," SAE Paper No. 2000-01-5563.